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THE SHORE-ZONE SYSTEM FOR LAKE TAHOE

A Report Prepared
for the
Tahoe Regional Planning Agency

Comprehensive Planning Grant: Project No. NEV P-30

The preparation of this report was financed in part through a comprehensive planning grant to the Tahoe Regional Planning Agency from the Department of Housing and Urban Development.

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Prepared by
Antony R. Orme, Consultant
Department of Geography, U.C.L.A.

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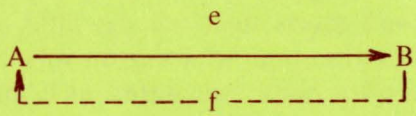
INTRODUCTION

This report has three principal objectives: to define the natural physical components that presently constitute the shore-zone system of Lake Tahoe, to assess the present impact of human activity on this physical shore-zone system, and to make general recommendations concerning future human activity within the shore-zone. Individual sections of this report are accordingly devoted to these three objectives.

The report is framed within a process-response model for the Lake Tahoe shore-zone. The process-response model consists of four elements: initial state (A), energy (e), response (B), and feedback (f), and may be expressed thus:



Within a shore-zone, the initial state is reflected by the geometry and materials of the shore-zone. The energy components comprise wave action, current action, periodic and non-periodic fluctuations of water level, and wind effects on the backshore. The impact of energy on the initial state produces a response in the geometry and materials of the shore-zone. When energy factors deviate significantly from their mean values, a new state is created which, by feedback, becomes the new initial state for subsequent shore-zone development. When energy factors remain reasonably constant over a period of time, a dynamic equilibrium is established in which the energy, materials, and geometry of the shore-zone are more or less mutually adjusted. Under natural conditions, the tendency towards dynamic equilibrium manifests itself at all times, though the tendency may be temporarily disrupted by exceptional inputs of energy or materials from beyond the shore-zone. Under artificial conditions, that is,under conditions shaped by man, disruption may be more permanent. This theme is pursued in later sections.

A shore-zone is an open system, conditioned in part by the exchange of energy and materials with the neighboring environment, and in part by the system's own capacity for internal regulation. Thus the shore-zone of Lake Tahoe cannot be examined in total isolation. It must be viewed as a dynamic zone that intervenes between the inland watersheds and the deeper portions of the lake. The watersheds are sources of both energy and materials, and any interference with them will generate changes in the shore-zone. The lake waters provide fetch for wind-generated waves and currents, while the deeper portions of the lake form receptacles into which shore-zone materials may be lost. Disturbance of the lake system, for instance by dredging or construction close to shore, may likewise generate changes in the shore-zone.

The present report defines the *shore-zone* as comprising the following:

(a) *a nearshore zone:* This zone extends from the lake surface down to a depth of -30 feet. It varies in width from 0 to 1400 yards.

(b) *the foreshore:* a zone of wave run-up above the lake surface. Because the lake surface ranges in elevation from 6,223 to 6,229 feet above sea level, depending on the quantity of inflow and the operation of gates in the Tahoe City outlet dam, the foreshore moves up and down within narrow limits. It is also affected by seiche oscillations.

(c) *The backshore*: a zone lying above the limits of normal wave run-up wherein beach materials are subject to wind winnowing and to colonization by land vegetation. This zone may be eroded by storm waves.

The *offshore zone* begins at an arbitrary depth of -30 feet and extends out into the lake. Steep cliffs commonly occur at or near the inner edge of the offshore zone. The above definitions differ from those normally used along open, tidal coasts,but are well suited to the observed characteristics of Lake Tahoe.

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THE NATURAL SYSTEM

Lake Tahoe is an irregular oval, 22 miles long from north to south and up to 12 miles wide. It occupies a surface area of 191 square miles within a contributing watershed area of 315 square miles (exclusive of the lake). Its greatest measured depth is 1,645 feet and it contains approximately 122 million acre-feet of water. The shoreline measures 71 miles in length, of which 42 miles lie in California and 29 miles in Nevada.

INITIAL STATE

Within the framework of a process-response model, the initial state of the shore-zone of Lake Tahoe may be defined in terms of its geometry and constituent materials. These in turn reflect the geologic and geomorphic development of the Lake Tahoe basin.

Shore-zone Geometry

Lake Tahoe occupies a portion of a down-faulted trough between the Sierra Nevada to the west and the Carson Range to the east. Although the fault scarps have been much modified by weathering, erosion, and volcanic activity, major north-south faults still exert strong influence on portions of the shore-zone and offshore region. The entire east shore of the lake was seemingly blocked out by faulting, reflected in the steep western flanks of the Carson Range which rises some 3,000 feet above lake level within three miles of the shore. This relief contributes considerable potential energy to streams flowing from the Range to the lake,and suggests that interference with these watersheds would cause a major increase in sediment delivered to the shore-zone. Furthermore, faulting is also responsible for the continuous line of cliffs and steep slopes above 20° that lies beneath the lake at or just beyond the outer edge of the nearshore zone (Figure 1). Consequently, sediment delivered to the shore-zone down the western flanks of the Carson Range has a relatively high probability of being lost over the offshore cliffs into deep water.

Faulting has also created precipitous shore-zone slopes elsewhere around the lake, notably along the western margins of Crystal Bay running out beyond Stateline Point, behind Carnelian Bay running out beyond Dollar Point, and along the coast south of Rubicon Point. In each of these three localities, steep hillsides plunge beneath lake level and are more or less continued in precipitous offshore cliffs. Lacking a shore-zone shelf, these sections of coast favor direct loss of materials into the deeper parts of the lake. Other portions of the offshore cliffline shown in Figure 1 may also be fault-guided, but some cliffs are known to represent the steep submerged flanks of glacial moraines. Offshore at Tahoe City, it seems likely that successive lava flows contribute to a stepped cliffline. In these latter areas however, the shore-zone shelf is commonly much wider and the cliffs lie farther offshore.

The approximately oval shape of Lake Tahoe is rendered irregular by a number of bays and inlets. The most pronounced irregularity in the shoreline is Emerald Bay, which covers about 460 acres at the southwest corner of the lake. Emerald Bay is flanked by steep lateral moraines and maintains contact with the main lake through a narrow strait, 8 feet deep at its shallowest point, which appears to represent a breached recessional moraine. Other irregular features along the west shore include Rubicon Bay, Meeks Bay, and the much broader McKinney Bay with its extension around to Dollar Point. The north shore contains Carnelian Bay, Agate Bay, and Crystal Bay. The east shore is comparatively straight but contains several small coves and harbors, the largest of which is Glenbrook Bay. The south shore forms a broad curve broken by the mouths of the Upper Truckee River and Trout Creek, by Taylor Creek, and some smaller streams.

The width of the shore-zone varies considerably around the lake. It is widest along the south shore and again off Tahoe City at the northwest end of the lake. In both these localities, the edge of the nearshore shelf lies up to 1,400 yards from the shore (Figure 1). The significance of these broad shelves is that they both form a depository for sediments reaching them. Indeed the broad shelf at the south end of the lake is probably composed of Pleistocene and Holocene sediments to considerable depth. The Tahoe City shelf is largely composed of bedrock, presumably lava flows. Elsewhere around the lake, the shore-zone is much narrower and, as has been pointed out, is locally pinched out where steep cliffs plunge into the lake. In Rubicon Bay and Agate Bay, however, the shore-zone is up to 600 yards wide before the -30 foot contour is reached. Marla Cove and Logan Shoals provide a shore-zone up to 800 yards wide on the east shore, but these are exceptions to the normally steep shore-zone.

A final fact that deserves note at this stage is the existence of steep-walled canyons notched into the offshore cliffs just beyond the shore-zone. Canyons are found in the southern part of the lake between Elk Point and Eagle Point, along the west side between Rubicon Point and Sugar Pine Point, and offshore at Crystal Bay. They may occur elsewhere. Their origin is not clear but it seems reasonably certain that those between Rubicon Point and Sugar Pine Point are the offshore extensions of former glacier passageways, contained within flanking lateral moraines. The same explanation may hold for the deep narrow canyons in the southeast corner of the lake, where one submerged ridge separating two canyons is at least 400 feet high. These and others farther west may have been modified by subsurface density or turbidity currents, triggered by the outflow of drainage from the Upper Truckee River. Regardless of their origin, these canyons are of significance because they frequently bite deeply into the offshore cliffs and head in towards the shore before terminating in 30 or 40 feet of water. They represent funnels through which shore-zone sediments of suitable size might be channeled into deeper water, and thus lost to the shore-zone system.

Shore-zone Materials

The materials contributing to the shore-zone are important because their composition indicates their probable source, and because their grain-size parameters suggest how they may behave under varying energy conditions.

Materials contributing to the beaches around Lake Tahoe derive from three main sources: from the 70 or more streams that drain the Tahoe basin watersheds, from the erosion of cliffs around the lake, and from the gravitational mass movement of materials from nearby hillsides directly into the lake. Of these, the first source is undoubtedly the most significant, whereas the last source is comparatively unimportant under natural conditions. The delivery rate of materials to the lake from all three sources may be grossly upset by human activity. Other sources that sometimes contribute materials to ocean coasts are irrelevant in the present context.

The estimated average annual flow of water from basin watersheds into Lake Tahoe is 312,000 acre feet, of which 43 per cent is contributed by the Upper Truckee River (60,000 acre feet), Trout Creek (43,000), and Taylor Creek (30,000) flowing into the south end of the lake. Streams entering along the west side, between Taylor Creek and Tahoe City, contribute a further 126,000 acre feet or 41 per cent. The north and east side streams contribute the remaining 16 per cent. Consequently, streams draining from the rugged glaciated southern and western portions of the basin contribute 84 per cent of the inflow from an area that also has abundant materials (in the form of glacial and fluvioglacial debris and weathered rock) available for transport.

Under natural conditions, the streams entering Lake Tahoe carry between 0.13 and 0.34 tons of sediment per acre-foot of inflow, or 40,000 to 100,000 tons per year on average (USGS Water Supply Paper 1972). Because the Truckee River outlet probably carries away not more than 0.06 to 0.13 tons of suspended sediment per acre foot (or 10,000 to 25,000 tons per year), it seems likely that the majority of this material settles in the lake and around its shores. In addition, streamflow contributes organic material to the lake, ranging in size from floating tree trunks, through decaying leaves and bark, down to particles of microscopic size. Until these organic materials decay to form gases, they also represent solids for deposition in the shore-zone and adjacent lake.

Examination of the shore-zone at the south end of the lake supports these contentions. The beaches are composed of granitic waste of sand, granule, and small pebble size. The sand fraction contains much magnetite, presumably also derived from granite waste. The nearshore shelf is underlain by much sand-size granitic waste veneered with organic detritus. This sand becomes finer towards the outer edge of the shelf, macroscopic organic detritus becomes less common, and a flocculent mud predominates to depths of at least -50 feet down the offshore cliff. These deposits were presumably introduced to the shore-zone by the Upper Truckee River and neighboring streams. Under natural conditions, Truckee Marsh would have served as a settling reservoir for much of the stream-borne sediment and would have been built out slowly towards the lake. The temperature contrast between the Upper Truckee River and the Lake probably generates a density current that helps to transport the finer silt and clay size material towards deeper water. For example, in April the river has a temperature of about 3°C whereas the lake's temperature lies around 5°C (and increases rapidly to as much as 20°C at the surface in the summer, and to 22-24°C in Tahoe Keys). The inflow of colder denser water probably establishes a bottom current and similar currents operating elsewhere on the shelf may help move appreciable amounts of finer material towards deeper water, even to the heads of the offshore canyons and to the cliff edge. It seems likely that a considerable portion of the shelf has been built up of fluvial (or earlier fluvioglacial) debris and is perhaps more amenable to change than other parts of the shore-zone where rock occurs at no great depth.

Throughout much of the west shore, north to Tahoe City, the beaches are composed of coarse sand and small to medium size pebbles, alternating with sections composed of large pebbles and cobbles (Figure 2). This heterogeneity of size is a reflection of the morainic and outwash terrain that occupies much of the west shore and its hinterland. Streams such as General Creek, McKinney Creek, and Ward Creek bring a wide range of materials to the shore, ranging from boulders and cobbles in times of peak snowmelt, to silts and clays during stages of low discharge. Ward Creek has built a broad lobate delta with this debris, while a distinct plume of finer materials can be traced out into the lake. These streams also introduce much organic debris to the lake. Materials of sand size and larger are generally confined to the beach and nearshore areas, but where the offshore cliff comes close to shore, for example south of Rubicon Point, they are also found plunging down towards greater depths. Commonly, however,

the offshore cliff is mantled with silt and clay-size materials lying at steep angles. Off Tahoe Pines and Homewood, the shore-zone is very narrow and the outer edge of the nearshore shelf lies between 100 and 200 yards of the shore, the offshore cliff cresting in less than 20 feet of water and then plunging to depths of over 500 feet, with a 20° slope or greater. The clay-silt and organic mix that mantles this cliff forms an ideal habitat for the crayfish that build their burrows here. Owing to the cliff's proximity to the shore and to numerous debris-laden streams, coarser sediment and organic debris often spills over the cliff edge into deeper water. At Sugar Pine Point, a shelf of sand, cobbles, and boulders extends for over a mile northwards before ending abruptly at about -60 feet. This feature is probably a submerged glacial moraine or a glacial outwash shelf. Farther south, off General Creek, Meeks Bay, and Rubicon Bay, offshore canyons head within 100 yards of shore.

From Tahoe Park to Dollar Point, the shore-zone is broad and shallow, and a gently-sloping rock shelf extends for between 2 and 3 miles into the lake (Figure 2). Much of this shelf lies between 35 and 50 feet below the lake, with pockets and rills descending a further 10 feet. These hollows contain sand and small cobbles. The shelf is also broken by steps 3 to 4 feet high. These appear to represent the edges of successive lava flows as, indeed, the entire shelf is seemingly composed of volcanic materials, overlain here and there by lacustrine clays and outwash remnants. The significance of this broad rock shelf to development within the shore-zone will be examined later.

The north shore-zone is underlain by a wide range of materials in terms of size, a reflection in part of the poorly sorted alluvial fan glomerates and other coarse Pleistocene deposits that lie behind Crystal and Agate Bays. Recent developments at Incline have accelerated the delivery of sediments to the lake by way of Incline and Third Creeks. Immediately north of Stateline and Dollar Points, solid rock forms the steep offshore cliff, and the narrow shore-zone is also rocky, with large boulders tumbled in among clean sand. Shingle of fine pebbles and coarse sand forms the beach at Carnelian Bay. Fine sand forms Kings Beach farther east. The only accumulations of Quaternary blown sand around the lake are to be found in modest dunes on either side of Griff Creek at Kings Beach. These deposits are a significant testimony to the prevailing southwesterly winds within the lake basin and are found in a predictable site.

Most of the eastern shore-zone of the lake is characterized by cobbles and boulders of granite lying within a matrix of granitic sand, a reflection of the composition of the greater part of the neighboring Carson Range within the Tahoe basin. On the more open shores, the granite sand has frequently been swept away and the coast is armored with large granite boulders, many of which are core stones that have been pried loose from the weathered granites above the shore and have tumbled directly into the lake. Off Deadman Point, these boulders have tumbled over the crest of the offshore cliff into deep water, and this has probably happened at several other localities where the cliff comes close to the steeply sloping shore. Granite sand is found in the bays along this shore, for instance in Marla Bay, Glenbrook Bay, Skunk Harbor, and Secret Harbor. Past logging and sawmilling activities on the slopes of the Carson Range are reflected in the logs that lie submerged within the shore-zone, and in the sawdust and organic matter that appear in the cores of nearshore sand taken in Glenbrook Bay.

ENERGY FACTORS

In general, the principal energy factors affecting the Lake Tahoe shore-zone are waves and wave-induced currents, generated ultimately by winds blowing over the lake. Winds are also directly responsible for some winnowing in the backshore. Winds, waves, and currents are erratic and unstable, and the circulation patterns within the lake are complex in time and space. If one adds to this the fact

that boundary conditions around the lake are diverse and complex, it is evident that different portions of the shore-zone around the lake may experience radically different energy controls. A strong current sweeping across the rock shelf off Tahoe City may have little effect on the morphology of the shelf, but a current of similar magnitude in the southern part of the lake may lead to appreciable redistribution of the more mobile sediments. It should be emphasized, however, that the magnitude of energy available to the lake shore-zone is appreciably less than that affecting ocean coasts, and that the likely response of the shore-zone is accordingly reduced. There is as yet inadequate data concerning the long term effects of current action within the lake, but it seems likely that both wave-induced currents and density currents may move large amounts of finer material from the shore-zone into deeper water.

Wind

Prevailing winds over the lake are generally from west to east but local topographic conditions often impart northwesterly or southwesterly directions to them. Figure 3 indicates wind directions at Tahoe City which, for want of more complete data, must be considered roughly representative of the Tahoe basin. Prevailing winds lie in the southwest and west octants, which together provide 48.1 percent of the winds affecting the lake. At other localities around the lake, northwesterly winds often prevail. In general, the westerly character of these winds will generate wave action from the west which, in turn, should induce eastward-moving currents around the northern and southern ends of the lake. Maximum wind velocities generally occur during the passage of winter storm fronts, winds being from south to southwest ahead of the front,and from west to northwest after frontal passage. Maximum sustained winds probably do not exceed 40 to 45 knots during these storms but topographic conditions may encourage gusts of 70 to 90 knots during severe storms. In winter, northeast winds may become dominant for a time over the basin, encouraging strong onshore wave action along the western shore.

Light to moderate winds may also be produced by local solar heating in the absence of atmospheric disturbances from outside the region. Such winds are generally from the east in the early morning, shifting to south at mid-day, and to southwest in the afternoon – at which time they reach a maximum velocity of not more than 20 knots. These winds are less significant generators of wave and current action but, if anything, tend to reinforce the eastward motion of water across the lake during the afternoon. Calms are reported for 18.9 percent of the time, a relatively high incidence compared to open coasts.

Wave Action

Four factors contribute to wave generation: wind velocity, wind duration, fetch, and depth of water. In addition, wind direction will determine the initial movement of the wave form, although waves are subject to refraction and shoaling in shallow water. The strongest and most frequent winds come from the quadrant between northwest and southwest. Consequently, the strongest wave action is generated from this quadrant, and wave heights of up to 6 to 9 feet may be recorded from this direction. Maximum fetch within Lake Tahoe is afforded along the 22 mile north-south axis, but winds from these directions are infrequent. Minimum fetch is afforded from east to west; consequently, waves generated by westerly winds may have limited opportunity to acquire maximum dimensions before hitting the east shore. The fetch for northwesterly and southwesterly winds is about 17 and 15 miles respectively – thus waves generated along these axes by the prevailing northwesterly or southwesterly winds are likely to be of maximum proportions for Lake Tahoe. The southeast shore is thus likely to experience strong wave action, while those portions of the north shore that face towards the

southwest are also likely to feel strong wave effects. These are theoretical conclusions based on wind and fetch data. They also accord well with field observations, although it is emphasized that winds from any quadrant may generate locally dominant waves.

Waves generated over the deeper portions of Lake Tahoe become greatly modified on entering shallow water, that is,water whose depth is less than half the wave length. Wave height increases as wave length and velocity decrease. Wave energy is lost through bottom friction and through the actual infiltration of the wave motion into the semi-fluid mass of suspended sediments at or near the lake bottom. This loss of kinetic energy towards the wave base is partly compensated by an increase in potential energy at the wave crest. The crest becomes narrower and sharper, and the wave breaks when the velocity of water particles at the wave crest exceeds the decreasing velocity of the wave form. This commonly occurs when the depth of water is 4/3 the wave height at the break point. Clearly, therefore, the depth of water and the morphology of the nearshore lake bottom are of critical importance to the positioning of the break point of a given wave. The deeper the water in the nearshore zone, the nearer the shore the waves will break. As most beaches around Lake Tahoe shelve steeply to about -6 to -12 feet, and as most waves are of comparatively short length, waves tend to break close to the shore. There is frequently no surf zone between the breaker and the shore and the breaking wave runs directly up the beach as swash. Where the nearshore zone is shallow for some distance offshore or where storm waves develop, the breakers may lie some distance from the shore, a surf zone develops shoreward of the breakers and wave-induced currents are accordingly more significant. Such conditions are most likely to occur around the southern margins of the lake, with westerly winds prevailing. They may also occur along the shallower portions of the north shore from Tahoe City to Incline.

Although wave forms in the shallow waters around Lake Tahoe are considerably smaller in mean magnitude than those on ocean coasts, wind action may rapidly generate waves of high frequency. Waves with a frequency of between 18 and 25 a minute were observed to strike the shore within one hour of the start of moderate to strong winds over the lake. This frequency is between 1.5 and 2.0 times the frequency of destructive waves along an ocean coast. It is likely therefore that what the Tahoe waves lack in magnitude they make up for in frequency. Thus, despite their relatively modest proportions, waves on Lake Tahoe should not be underestimated as forces of erosion and current generation. Wave motion was observed to be responsible for sediment motion and ripple formation in the nearshore zone to depths of at least -12 to -15 feet.

Wave-induced Currents

The movement of water in lakes is usually turbulent; that is,at any point in a lake, variable movements in any direction may be observed in addition to any mean directional flow. These variable movements are essentially random velocity components which permit the transfer of energy and materials in any direction and also increase the apparent viscosity of the water. This last point helps to explain the importance of currents generated by the wind and waves. Without this viscosity, such currents would have only shallow effect.

The principal currents affecting Lake Tahoe are: general circulation currents, wind-induced surface drift, wave-induced currents, density currents, and seiche-related currents. The inter-relationship of these currents is exceedingly complex and not presently well understood. However, in the present context, the wave-induced currents are certainly the most important and will be discussed in more detail than the other currents.

The orbital movement of water particles in finite waves is open, resulting in two fluid motions: the orbital velocity of the water particles themselves, and the mass transport velocity (or net particle drift) of water in the direction of wave motion. The latter becomes part of the nearshore wave-induced current system and produces a shoreward mass transport of water. Water cannot continue to pile up against the shore, however, and must therefore be compensated by a return flow towards deeper water. This return flow may occupy a broad zone within the nearshore zone, or it may occur at discrete locations along the shore in concentrated high-velocity filaments called rip currents. The nature of this return flow in Lake Tahoe is presently undetermined, but it must be considered as a mechanism which, along with density currents, may remove beach materials to greater depth.

When waves break at an angle to the shoreline, the nearshore current system becomes more complex. To the above-mentioned shoreward mass transport and return flow of water, is added a longshore component of momentum – the so-called longshore current. This current develops within the surf zone where it exists, or beyond the breakers where the break point is close inshore. It may be superimposed upon the inner portion of a general circulation current or may exist independently. For a given value of wave energy and wave steepness, this longshore component develops best when the waves approach the shore at an angle of about 40°. Thus westerly winds would generate strong longshore drift on both the north and south shores of the lake, with a resultant movement of materials to the east.

Density Currents

These are important bottom sweeping currents caused by cold and/or sediment-laden waters moving into and under the main body of the lake. They are important where there is a significant inflow of comparatively cold water into the lake, notably at intervals along the south and west shores where cold, debris-laden streams from the Sierra Nevada enter the lake. Although coarser sediments are soon dumped in the nearshore zone, finer materials may be carried out over the offshore cliff or down the canyons. The form of these latter features may have been modified by density currents.

Wind Drift and Seiche Currents

Wind blowing over the lake surface generates a shallow surface drift through stress on the water. This leads to disturbance of the surface waters and may alter density distributions. Generally, these currents are too weak to affect sediment transport significantly and, in any case, their effect near the shore is obscured or absorbed by stronger currents.

Wind drift does, however, lead to a slight piling up of water at the downwind end of the lake and, when this piling of water ceases, a return flow is set up to return water to the upwind end. Since in this process the momentum is not lost, a new flow starts at the old upwind end until a periodic rocking motion or seiche is produced. Seiches may also be produced by sudden changes in barometric pressure or by landslides. The maximum range of the seiche on Lake Tahoe has been measured in one locality, Pope Beach, as 26mm (approximately one inch) and the mean was recorded as 3.8 mm. It is concluded that these seiches will be of only minor importance to the mass movement of water within the shore-zone in comparison with surface waves.

RESPONSE ELEMENTS

The response of the initial geometry and materials of the shore-zone to the above energy factors can be examined in terms of erosion, transport, and deposition within and beyond the shore-zone. Except

in conditions where dynamic equilibrium is maintained, these responses will be reflected in the changing geometry and material characteristics of the shore-zone. The changes will,in turn,provide new conditions for the subsequent operation of energy factors.

Erosion

Erosion of the shore will be accomplished by wave action and will be most pronounced where unconsolidated materials are exposed to high energy waves. Such conditions are found, for example, at El Dorado Beach fronting on South Lake Tahoe. The shore is composed of 25 foot high cliffs of fluvioglacial outwash that yield comparatively readily to erosion and slumping, and are exposed to attack by waves generated over 17 miles of fetch. Similar materials occur at intervals along the west shore and, although wave fetch is less, the strong northeast winds of winter may cut into this shore, removing beach materials and cutting cliffs in the less competent glacial and fluvioglacial debris. In contrast, those shores formed of bedrock are more competent to resist erosion. Thus the fault-controlled coasts north of Stateline and Dollar Points, and south of Rubicon Point are slow to change. The east shore is in large measure protected from severe erosion by its shoreline armor of granite boulders which tend to absorb much wave energy, though it seems likely that large volumes of granitic sand have been removed from the shore-zone into deeper water by wave and current action.

It should be emphasized at this point that erosion, transportation, and deposition are basic components of all shore-zone systems under natural conditions. These components tend to balance each other – erosion providing beach materials that tend to counter further erosion by absorbing wave energy. It is also evident that under natural conditions shorelines tend to grow by net accretion rather than lose material from net erosion. In this process, a redistribution of materials within the shore-zone is essential. Excessive erosion in one locality is commonly countered by deposition elsewhere. Thus, any interference with this sequence of events is likely to trigger changes throughout the system.

Transport – Littoral Drift and the Nearshore Circulation System

Material eroded from cliffs and backshore slopes will remain on the beach for a while where it will absorb excessive wave energy. Its presence will not, however, curb the wind energy generating wave action. Thus, if winds persist, waves will eventually comb down the material stranded on the beach and remove it into the nearshore zone. Within the nearshore zone, this cliff debris, together with any materials derived from nearby streams, will be exposed to littoral drift, that is to movement along the shore, or to removal into the offshore zone.

Littoral drift is a complex response to wave and current energy acting on materials that are free to move within the shore-zone. Where waves break close inshore and run up the beach as swash, successive waves will cause individual sand grains to move in zig-zag fashion along the foreshore, provided waves approach the shore at an oblique angle. Where waves break some distance from the shore, the longshore current established within the surf zone will also move materials along the shore. Figure 4 indicates the predominant littoral drift and nearshore circulation pattern for Lake Tahoe, deduced from observations on unconsolidated sediments in the shore-zone. Along the west shore, south of Tahoe City, movement is generally southwards, and this anticlockwise motion continues around the south shore to at least as far as Elk Point, and probably to Zephyr Point. This pattern represents the predictable response for drift generated by wind and wave action in this part of the lake. The north shore exhibits a similarly predictable clockwise drift to the east, continuing down the east shore as a southward drift. It is emphasized that these patterns represent the predominant drift, not the drift that may necessarily be observed at any one time. Littoral drift may be reversed by

temporarily dominant winds, for example from the northeast, and much material in transit through the shore-zone may be returned towards its immediate source. There may be other patterns of a random nature superposed on the drift, while density currents may also disturb the general circulation. Furthermore, this is the pattern exhibited by sediments and it is not therefore necessary for each drift component to run into the next one ahead. Indeed, it seems likely that materials moving around the south shore must inevitably end up by being moved towards the canyons and cliffs offshore. Similar movement of materials over the offshore cliffs probably occurs at the southeast end of McKinney Bay off Sugar Pine Point, and also off Dollar Point, Stateline Point, and Sand Point in the northern portions of the lake. These cliffs and canyons must therefore be considered as zones in which materials can be lost from the shore-zone system. The outer, deep-water portions of the circulation patterns shown in Figure 4 for the Crystal Bay, Agate Bay, and Tahoe City sub-systems are hypothetical but consistent with circulation patterns in certain other lakes.

Littoral drift is not confined to the zone shoreward of the breaker line but also occurs beyond the breakers where the longshore current affects the return flow of water and finer sediments. It is probable that some littoral movement of material takes place to depths of -30 feet or more. Strong littoral drift depends on the magnitude and direction of wave energy, the angle of wave attack, and on wave steepness (the ratio of height to length). Waves with a steepness of about 0.025 produce optimum conditions for littoral drift, with drift decreasing as the ratio increases or decreases away from this value. As the ratio increases with steepening waves, the littoral component of sediment transport decreases while the offshore component increases. Thus steep storm waves of high frequency may cause a predominant movement of sediments down the beach and out across the nearshore zone to the offshore cliffs, especially when waves attack nearly normal to the shore.

Deposition

Solid materials are introduced naturally to Lake Tahoe by inflowing streams, by cliff erosion, and by direct gravitational mass movement down hillslopes immediately above the shore. Within the shore-zone, these materials are either redistributed by littoral drift or moved directly across the nearshore shelf towards deeper water and thus lost, at least from the shore-zone system. Whether or not these materials are lost from the system, and the extent to which they may be redistributed by littoral drift, depend on two factors: the settling velocity of the individual particles, and the critical tractive forces available. Settling velocity is determined by the size, sphericity, and density of the particles, but primarily by the size. Other things being equal, large materials tend to remain near their source while smaller particles may move considerable distances. Critical tractive force is directly proportional to velocity, so that the greater the current velocity, the greater chance a particle has of being transported. The redistribution of sediments around Lake Tahoe generally reflects these principles. Relatively coarse materials from sand to boulder size comprise the beaches, sands and finer materials occur farther out on the nearshore shelf, and mainly silts and clays occur beyond the crest of the offshore cliffs. Thus materials that are introduced to the nearshore system, either naturally or by man, tend sooner or later to find the niche for which nature has destined them. This may explain why 80 million cubic yards of sand brought down by the old railway to create a beach at Tahoe Tavern eventually moved into a pocket on the rock shelf some distance from shore – its grain-size parameters probably differed from those necessary to sustain a beach along the immediate shore under existing conditions. This point will be examined later.

The area of greatest deposition around the present shore-zone lies at the mouth of the Upper Truckee River and Trout Creek, and more especially in the zone immediately east, or downdrift, from the mouth. Although this sedimentary wedge may be increasing slowly in volume, it is likely that the

movement of additional materials into the lake from the watersheds is largely compensated by a movement of earlier materials out of the zone and down the neighboring canyons and cliffs. In this way, a quasi-dynamic equilibrium is maintained. Long term measurements are of course needed before this fact can be substantiated. Similar near balances between the input and output of materials from the shore-zone appear indicated in other portions of the lake where relatively natural conditions still prevail. Where man has disturbed the system, however, very different conditions prevail. These will now be examined.

MAN'S INFLUENCE ON THE SHORE-ZONE SYSTEM

Man is an erratic and unpredictable energy factor. As such, he either augments or counteracts natural energy factors in order to derive some real or imagined benefit for himself and his fellow men. He introduces new structures and materials to the shore-zone, removes existing forms and materials from the shore-zone, and in either instance disrupts the existing system. He also influences the nature and magnitude of processes that shape the watersheds behind the shore, and, in this way, indirectly augments or reduces the supply of energy and materials to the lake. Not all human activities are necessarily grossly disruptive of the natural system,but it is evident that many past and present actions of man in and around Lake Tahoe have generated unscheduled responses. We may thus consider man as an additional energy force that in some way modifies the response elements in our model, for good or for bad.

There are three principal ways in which man has so far influenced the physical shore-zone system around Lake Tahoe: by regulation of the outlet waters, by interference with the contributing watersheds around the lake, and by direct manipulation of the shore-zone.

Regulation of the Truckee River Outflow

The natural level of the outlet of the lake is about 6,223 feet. Since 1874, however, water outflow has been regulated by the operation of gates in a low dam located on the Truckee River outlet at Tahoe City. The maximum water level is set at 6,229 feet. The quantity of water subject to regulation between 6,223 and 6,229 feet is about 745,000 acre-feet. The lowest known level of the lake during historic times was 6,221.74 feet in December 1934, and the highest known level was 6,231.26 feet in July 1907.

Manipulation of the outlet level between 6,223 and 6,229 feet can thus affect the positioning of the foreshore with respect to the shore-zone as a whole. While this is insignificant on the steep uninhabited sections of the lakeshore, the more gently sloping portions of the shore-zone may experience considerable oscillation of the shoreline. A study of the likely effects of changing lake level on the shore-zone was completed by Kenneth M. Turner (Lake Tahoe Stage-Beach Area Study, February 1959) and is available. In summary, the total shore area between elevations 6,220 and 6,229.5 was found to be 2,848 acres, of which 1,174 acres would be marshland (all in El Dorado County along the south shore) if the water level fell to the lower level. Reduction of the maximum water level to 6,228.5 would increase the minimum shore area by 108 acres, of which 80 would be marsh, 12 rock and cobble, and only 16 would form good recreation beach. The difference in shore area between the maximum lake stage of 6,229.1 feet set by the 1944 Truckee River Decree and the natural outlet at 6,223 feet is 1,868 acres, of which 1,110 acres would be marsh. Reduction of the lake level for the purpose of expanding recreational beaches is not, therefore, a reasonable proposition. There are, however, other advantages to reducing lake level by a modest amount – notably to reduce the storm wave hazard along shorefront properties.

Interference with the Tahoe Basin Watersheds

At present, the vast majority of watershed land lies beneath coniferous forest, much of it second stand timber that has grown since the native forest was clearcut for Virginia City mining and smelting purposes during the later nineteenth century. At that time, destruction of the forests greatly increased both the discharge and the sediment load carried by local rivers into the lake. Interference with the second growth timber on a similar scale would have dramatic impact on the shore-zone by increasing the amount of debris conveyed to the shore, either by streams or directly over surface slopes into the water.

Severe disturbance of the watersheds behind Incline Village is presently contributing large volumes of finer debris to the shore and creating a noteworthy plume of sediment at the mouths of Incline and Third Creeks. Similar plumes of debris, accentuated by suburban development in and around South Lake Tahoe, are noticeable around the southeast corner of the lake.

Whereas the theme of watershed interference is beyond the scope of the present report, it may be noted that much of the increased debris supply reaching the lake is of silt and clay size and thus settles beyond the beach areas. It is of no use for beach construction but, on the other hand, it does little harm to the physical environment of the beach. In contrast, the addition of abundant nutrients to the shore-zone generally may greatly accelerate the biological processes leading to eutrophication and excessive algae growths.

Direct Manipulation of the Shore-zone and Related Recommendations

Man's past and present manipulation of the shore-zone has taken three principal forms: the erection of barrier structures, the building of structures designed to modify the natural regimen of the shore-zone, and artificial beach nourishment. The impact of these features on the natural systems will now be examined in greater detail.

Barrier structures are walls, earthen banks, bulkheads, and revetments designed to prevent direct erosion or flooding of the backshore by reinforcing the interface between land and water. On ocean coasts, where high energy conditions may prevail, such structures are frequently of massive proportions. Around Lake Tahoe, where wave magnitude and shore-zone energy are generally less, such structures are accordingly less massive, and rubble revetments are the most common form of shore protection where erosion hazards are likely. Nevertheless, it is relevant to review briefly the advantages and disadvantages of each form of structure, so as to gain some insight as to the relative merit of each, and of alternative methods of erosion control.

Seawalls are generally massive gravity structures built of masonry or reinforced concrete. They are thus expensive to build and are used along open coasts only where economics dictate, for instance, to protect commercial development or major transport arteries. Their dimensions are dictated by the morphology of the area to be protected, though their height may be increased to prevent overtopping by storm seas. Overtopping may lead to undermining at the back of the seawall and to eventual collapse of the wall. Seawalls are designed to resist wave impact rather than to preserve the beach. When waves break against seawalls, the energy which throws water high into the air also allows it to return downward with similar force, thus eroding the beach near the base of the wall and removing it seaward. Erosion continues until the bottom material ceases to be affected by the downward velocities, but by then the foundations of both wall and beach may be exposed. Further, as the beach is removed

so deeper water penetrates closer inshore, wave energy becomes concentrated over shorter distances, and erosion intensifies. In short, loss of a beach is frequently the price paid for protection of the backshore. Such structures are rarely called for around Lake Tahoe and their undesirable effects suggest that they should not be used for shore protection.

Bulkheads are designed primarily to resist earth pressures from the back-shore, rather than to counter high wave energy. They are usually built with timber or metal sheeting held in place by piles, struts, and anchor structures, and serve to retain low bluffs that might otherwise collapse towards the water. Bulkheads also have their dimensions set by backshore morphology, and their height may be increased to prevent overtopping. They may generate similar beach erosion at their base to seawalls and, if the beach erodes, may be forced into a front line of defense against the waves. Bulkheads generally fail by falling seawards after damaging scour has undermined their base. One prominent steel bulkhead on Lake Tahoe is that designed to protect U.S. 50 on the clifftop behind El Dorado Beach (Figure 8). The fluvioglacial deposits forming the cliff along this stretch of shore are subject to wave erosion at their base, but, more significantly, to weathering and mass movement above the beach which attempt to reduce the cliffs to a gentler angle of repose. Nature has countered this tendency to cliff retreat with the roots of conifers and with a protective beach which prevents excessive wave scour at the cliff base. However, man has seemingly interfered with both these forms of natural protection, partly by interfering with the shore to the west and restricting beach replenishment through littoral drift, partly by destroying the vegetation. The effect of the bulkhead in restricting further cliff collapse is well shown by comparison with the unprotected cliff segment to the west (Figure 9). There is, however, a tendency towards beach erosion below the bulkhead under prevailing wave scour, and this can only be countered by artificially replenishing the beach in the future.

Revetments are sloping structures faced with stone or concrete blocks through which water may permeate. They are designed to protect bluffs and backshore developments from the ravages of waves and currents, and are the most commonly found form of barrier structure around Lake Tahoe. Because their sloping permeable structure absorbs much wave energy, wave run-up is reduced and beach scour at their base from reflected energy is appreciably less. They are frequently found around the lake where housing developments require protection, for example south of Tahoe Tavern, or where modest land reclamation has been initiated for recreation or parking facilities, for instance at Tahoe City. They generally exist at the expense of the local beach, and their presence does not generally promote beach growth.

In general, barrier structures protect backshore areas from the water but they do not prevent erosion of the foreshore, nor do they inhibit the removal of beach material, either along the shore or out into deeper water. Indeed, they frequently encourage beach erosion. For these reasons, such barriers may have a serious long-term effect on coastal development. For instance, as beach material is moved downdrift, barrier structures may prevent backshore sources from contributing new materials to beach replenishment. Where a barrier is short, such curtailment may be of little overall significance but, nevertheless, local beach loss may occur. Barrier structures are thus not the best form of shoreline defense and should be used only as a last resort, where less disruptive methods have failed or where protection of a backshore feature (such as U.S. 50) is of greater importance than beach preservation.

Groins, jetties, and breakwaters are structures designed to protect shores by modifying the natural regimen of the littoral zone. Alternatively, they are perhaps more commonly used in connection with harbor and marina development, though their use is not without certain undesirable aspects. Because littoral drift around Lake Tahoe is of such modest proportions, *groins* as such have not been built

specifically for the purposes of beach retention. However, groins, jetties, and shore-connected breakwaters have much in common and the effect of jetties on the shore-zone can be demonstrated at several locations around the lake. *Jetties* are commonly used to shelter inlets and harbor entrances from the undesirable aspects of littoral drift, namely clogging of their entrances with excessive sediment. They are also used to confine outgoing terrestrial drainage. Both uses are in evidence around Lake Tahoe. For example, with the development at Tahoe Keys along the south shore, it has been found necessary to construct rubble and steel piling jetties to protect the inlets, and also to channel outflowing drainage from the formerly more extensive Truckee Marsh. These structures are of very modest proportions and extend out into the lake to a water depth equivalent to the depth of the required channel. They are sufficiently high and impermeable to prevent materials being carried over into the channel. It is these characteristics, however, that are disturbing the natural pattern of littoral drift by encouraging accretion and partial storage of sediments on the updrift side of the updrift jetty (Figure 5). The jetties are sufficiently limited in length to allow sediments to work their way lakewards along the outer edge and to accumulate in the mouth of the inlet. From here, the material is either carried out into deeper water by outflowing terrestrial drainage or, when winds are blowing onshore, carried into the inlet to form bars of sand on both shores. This process is very evident at present at the most westerly outlet to the Tahoe Keys development (Figure 5), but is also observable at inlets farther east. The effect of this disruption is to deprive the beaches, on the downdrift (east) side of the downdrift jetties, of the materials that are necessary for the beach to maintain dynamic equilibrium. Some sand gets across these inlets but much is lost. This slow starvation of the downdrift beaches leads to progressive erosion and the formation of a nip or scar on the downdrift shore. Such scars were observed to have a magnitude of between 2 and 6 feet - which must be considered very significant in the Lake Tahoe shore-zone system. Similar downdrift erosion is noted on the downdrift side of other jetties around Lake Tahoe, for instance at the Lakeside Yacht and Harbor Club at South Lake Tahoe. It should be added that this disruptive feature of jetty and similar construction has long been recognized along the open coast, but that only in recent decades has the problem of downdrift beach starvation been largely overcome – by passing sand in pipelines under the inlets by means of pumps placed on the updrift side. It may be argued that such sand by-passing operations in Lake Tahoe would be akin to using a sledgehammer to drive home a small nail, and that such operations are unnecessary and, in any case, prohibitive in cost. Nevertheless, the construction of jetties and similar impermeable structures around the lake does create an erosion problem that can be clearly demonstrated in the field. It is modest in comparison with open coast erosion stemming from similar constructions, but in the rather delicate balance that seemingly exists between the input and output of materials within the shore-zone system, this erosion should be considered a disruptive and potentially degrading force. The construction of similar jetties or, more especially, of larger shore-connected breakwaters, should not in future be undertaken without prior careful analysis of the likely effects. Indeed, the construction of any large impermeable structure that is likely to deflect materials farther out from the shore, and possibly over the edge of the offshore cliff, should be avoided at all costs.

Offshore breakwaters on open coasts are generally built of heavy rubble parallel to the shore. Their length is roughly equivalent to the distance from the shore, so as to create, by means of wave refraction around such structures, an area of calm water to shoreward of their centers. This calm area normally shelters an anchorage or harbor entrance on the open coast, but may also shelter a safe swimming area, a use to which such structures are well suited in lake situations. An offshore breakwater may also be built so as to encourage deposition of littoral materials, normally in a bulge extending out from the shore opposite the center of the structure. In this way, beaches may be widened and the additional supply of materials thus trapped may be used for beach nourishment projects locally or in adjacent localities. As such bulges grow, they may serve as natural groins to trap a large expanse of beach updrift. This may, in turn, provide additional material for backshore, including sand dune,

development. An offshore breakwater near the Lakeside Yacht and Harbor Club demonstrates these effects well for Lake Tahoe (Figure 6). The breakwater is of a permeable nature, consisting of short piling sections separated by gaps in the length of the structure. A broad bulge has developed on the shore opposite and the beach area has been appreciably increased. A similar effect is observable behind an accumulation of rubble in the shallow offshore zone at Tahoe City (Figure 7). The beach has widened behind the rubble, but an erosion scar 6 feet high has developed downdrift and is presently cutting into the grassy backshore.

The most popular and most economic shore-protection device now used along sea coasts is the *artificially nourished beach.* A high, wide beach is now acknowledged to provide the most satisfactory solution to shoreline erosion problems. Thus a practice that attempts to maintain or restore the dynamic equilibrium of a beach is preferred to engineering structures that create artificial boundary conditions and generate unwanted side-effects. The practice also has the highly desirable quality of providing additional recreational space by extending the beach area, or at least rebuilding the beach area to its dimensions prior to any erosion. Artificial beach nourishment is seen by the present investigator as the principal solution to erosion problems and diminishing recreational space around several portions of the Lake Tahoe shoreline.

Artificial beach nourishment is not a process to be lightly conceived or executed. Clearly it would be futile to attempt artificial beach construction along those steeper portions of the shore-zone where deep water and offshore cliffs lie close to the beach. Such an artificial beach would soon be lost into the offshore deeps. Even in those areas where beach nourishment is reasonable, namely on the gently shelving portions of the north and south shores, careful attention must be given to both the existing qualities and materials of the shore-zone and to the grain-size parameters of the proposed beach fill. On a beach that is maintaining equilibrium behind a broad shallow shelf, additions to the beach may well be accomplished with borrow material of similar size characteristics. Shingle beaches may be fed with shingle, sand beaches with sand. On an eroding shore, however, it stands to reason that existing beach materials are incapable of sustaining the beach. Thus to add materials of similar size and range in this situation would be to invite continued erosion and the leakage of the beach fill into deeper water. There is, however, a positive linear relationship between grain size and beach slope – generally, the larger the grain size, the steeper the beach slope that may be sustained, so that pebble beaches are steeper than sand beaches. Thus on an eroding shore where shore-zone energy remains constant, successful beach nourishment will necessitate use of materials whose parameters, especially of grain size, exceed those of the original beach. This will produce a somewhat steeper beach profile in the foreshore and immediate nearshore zone, and the beach fill will thus converge on the old beach at shallow depth beneath the surface, preferably just beyond the depth of serious wave action. Fortunately, materials for artificial beach nourishment are readily available within the Tahoe basin from the range of glacial, alluvial, and expecially fluvioglacial deposits around the lake shores.

CONCLUSIONS AND SUMMARY RECOMMENDATIONS

The foregoing discussion has analyzed the shore-zone around Lake Tahoe in terms of a process-response model. The initial state and material components of the natural system have been examined, the various energy sources have been defined and ranked in order of significance, and the response of the shore-zone to inputs, transfers, and outputs of energy and materials has been assessed. The effect of human interference with this shore-zone system and its environment has then been determined, with particular emphasis given to the influence of constructional activity along the shore. Within this framework, suggestions and recommendations concerning the stability and use of the shore-zone have been made. In view of its high recreational value, the Tahoe basin will presumably experience further development of its tourist and residential potential in the years ahead. The shore-zone is likely to bear the brunt of much activity, and it is therefore necessary at this stage to summarize the salient conclusions to be drawn from the above study. Hopefully, in this way some of the errors of the past may be avoided, undesirable or dangerous developments may be excluded from future plans, and the shore-zone may develop along rational lines that accomplish a fine balance between the demand for further recreational and residential facilities and the conservation of the environment bequeathed by nature.

Two general recommendations are made. First, the shore-zone must be viewed within an open system framework. The shore-zone is not only dynamic but reacts readily to transfers and exchanges of energy and materials with the environment that surrounds it. In particular, potential developments within the watersheds that contribute to the lake must be viewed with respect to their influence on the shore-zone. Extensive deforestation or suburban tract development behind the shore may grossly increase the supply of materials reaching the lake, leading to physical clogging of the shore-zone system under present energy conditions, and to biological eutrophication of the lake environment at a rate in excess of natural processes. Dredging in the nearshore or offshore zone, or the construction of artificial islands and other features in the nearshore area, should be strictly avoided in the vast majority of situations, as these acts are likely to trigger unwanted responses at the shoreline. Furthermore, to view the shore-zone as an open system implies the existence within the system of interdependent sub-systems. Therefore, developments along one stretch of shore should not be allowed to go forward until a careful appraisal of their effects on neighboring shores has been made. This is particularly important with respect to downdrift situations where, for example, the effects of erosion scars triggered by some updrift construction are likely to be felt.

Secondly, before any individual development project is allowed to proceed on the ground, a careful examination of the existing system, and of the probable effects of various design structures on the system, must be made. This report has already examined these aspects in general but some conclusions must remain theoretical in the absence of quantitative data that is spatially and temporally significant. Detailed measurements should be sought for: the morphology of the shore-zone; the nature, magnitude, and periodicity of shore-zone energy; the origin, nature, and volume of materials available to the shore-zone; the regimen of freshwater drainage flowing to the lake; the direction, rate, and

variability of littoral drift; and the rate of shore-zone change-over time, under both natural and artificial conditions. Seasonal or non-periodic reversals in the movement of littoral materials must be considered in order to define the resultant of these opposing forces and, thereby, the predominant direction of material transport from which existing and projected values for supply and loss of materials can be quantitatively defined. With respect to individual structures, it is important to define a design wave (usually the mean of the highest one-third of the waves in the spectrum, including a selected storm surge), the design water level of the lake (between 6,223 and 6,229 feet), the foundation condition, and the construction materials, and then to adjust the design to minimize the unwanted disruption of the natural system.

In the light of all foregoing discussion, shore-zone localities that appear amenable to and will sustain development of harbors or marinas or similar development may be ranked as follows (the most suitable first):

(a) The Tahoe City rock shelf between Tahoe Tavern and Lake Forest, and extending out into the lake for at least one-half mile. This broad rock shelf should sustain development with minimum disturbance of the natural system. Development is possible beyond Lake Forest, but the cliff that runs south from Dollar Point should be avoided, as it probably exerts increasing effect on shore-zone processes nearer to its crest.

(b) The South Lake Tahoe shelf from Camp Richardson to Stateline. Beyond these limits, the shelf narrows rapidly, sediment loss is increased offshore, and space for development without disruption is negligible. Within these limits, careful note should be taken of the nature and effect of the offshore canyons and cliff on sediment loss. The shoreline in this area is amenable to artificial nourishment for recreation space.

It should be emphasized that the South Lake Tahoe shelf is developed in very different materials than the Tahoe City shelf. The former is composed, at least in its upper portions, of Quaternary sediments that are amenable to appreciable redistribution within and out of the system. No structure should be built on this shelf that is likely to accelerate the movement of materials outwards towards the canyons and cliff, triggering a possible comb down of beach materials along the shore. Localities (a) and (b) represent optimum localities for development around Lake Tahoe, but development should take note of previous comments. (c) Agate Bay between Flick Point and Brockway Rocks (short of Stateline Point) offers a third area for development for, although the nearshore shelf is narrower than in the above, there is a comparatively gentle slope into deeper water. Localities (a) and (b) and (c) would appear to offer attractive sites for development from the economic and engineering viewpoint, although more detailed analysis of bottom characteristics is required. (d) Certain small bays on the east and west shores offer reasonably safe conditions for restricted development of the shore-zone. These are Marla Bay, Zephyr Cove, Glenbrook Bay, and Sand Cove on the east shore; and that portion of McKinney Bay north of Sugar Pine Point on the west shore. Meeks Bay and the north portion of Rubicon Bay offer possibilities for very limited development, but are restricted owing to the many canyons that head close inshore. It would seem reasonable to discourage development in this (d) category in view of the larger areas available within the earlier categories. (e) Development is not advised for those stretches of shore-zone remaining, that is for those stretches not mentioned above, except in the form of floating or highly permeable structures that are not likely to disrupt shore-zone processes. Piers in well-spaced pilings, although aesthetically disturbing when frequently built along a shore, are not disruptive of these processes. Such structures should, however, be wholly permeable to the backshore so that beach material can move through them along the shore.

In conclusion, it is emphasized that construction within the shore-zone generally should minimize the use of impermeable structures such as rock or steel piling jetties, and should exclude their use

completely from unstable localities (all localities excepting (a), (b) and (c) above, for large jetties). Permeable jetties and breakwaters are to be favored for marina or harbor development in all areas. Shore protection is best afforded by natural beaches, and everything should be done to minimize disturbance of these beaches.

Where beach erosion is a serious hazard, either from natural causes or from human interference, shore protection will be best afforded by artificial beach nourishment – taking care to design the artificial beach with attention to grain-size parameters and optimum slope requirements. Artificial beach nourishment should also be considered as a means of extending recreational beach areas in safe localities, for example, off South Lake Tahoe. Materials for such nourishment are easily located within the abundant fluvioglacial and similar sediments around the basin, for example, in the deposits flanking the Truckee River immediately west of Tahoe City.

Acknowledgment: The author is grateful to Robert C. Richards of the University of California, Davis, Limnology Project, Lake Tahoe, for verbal data concerning the nature of bottom sediments in the nearshore zone. He is also grateful to Dr. Robert G. Bailey for valuable discussion in the field.

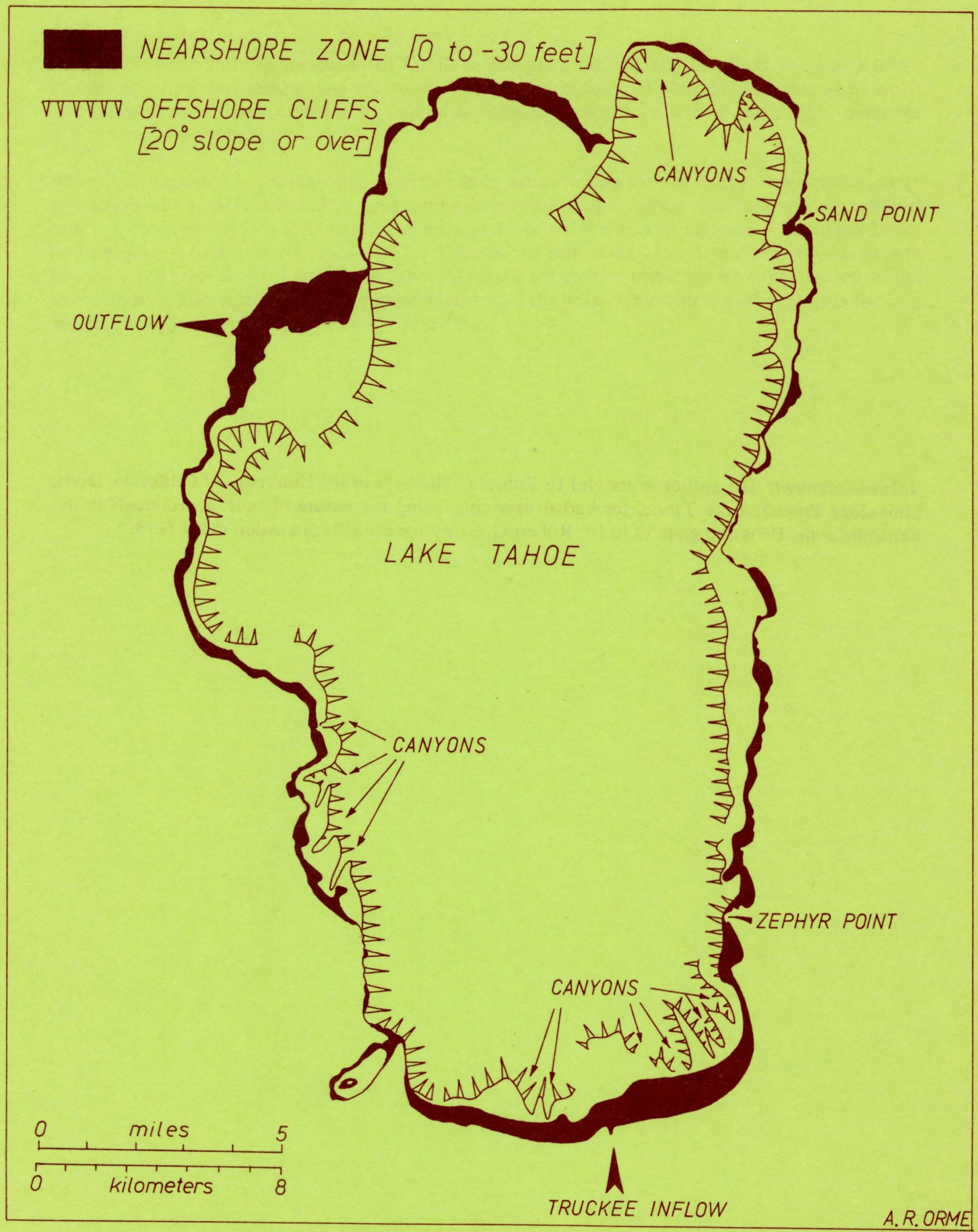


Figure 1. NEARSHORE MORPHOLOGY

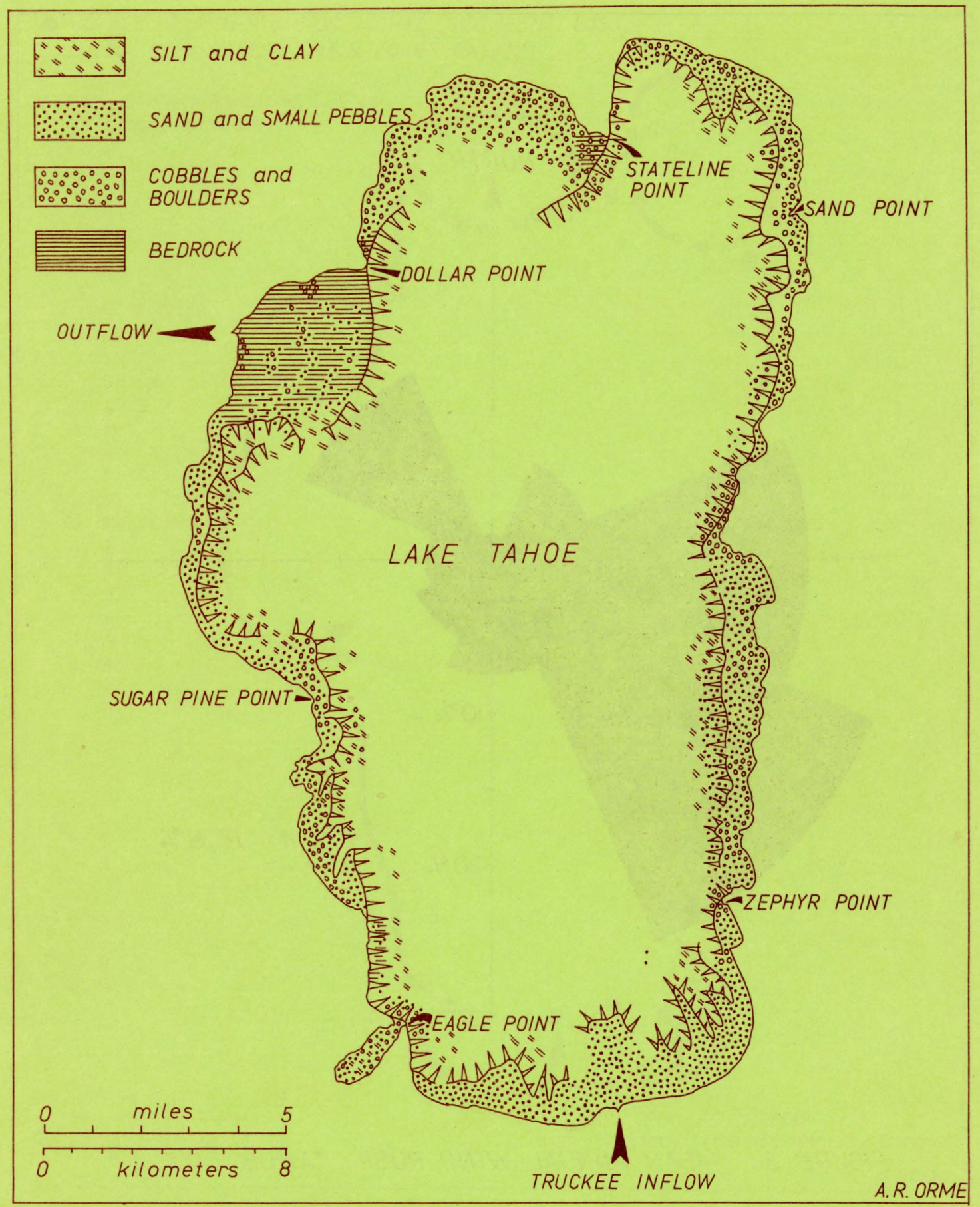


Figure 2. NEARSHORE MATERIALS

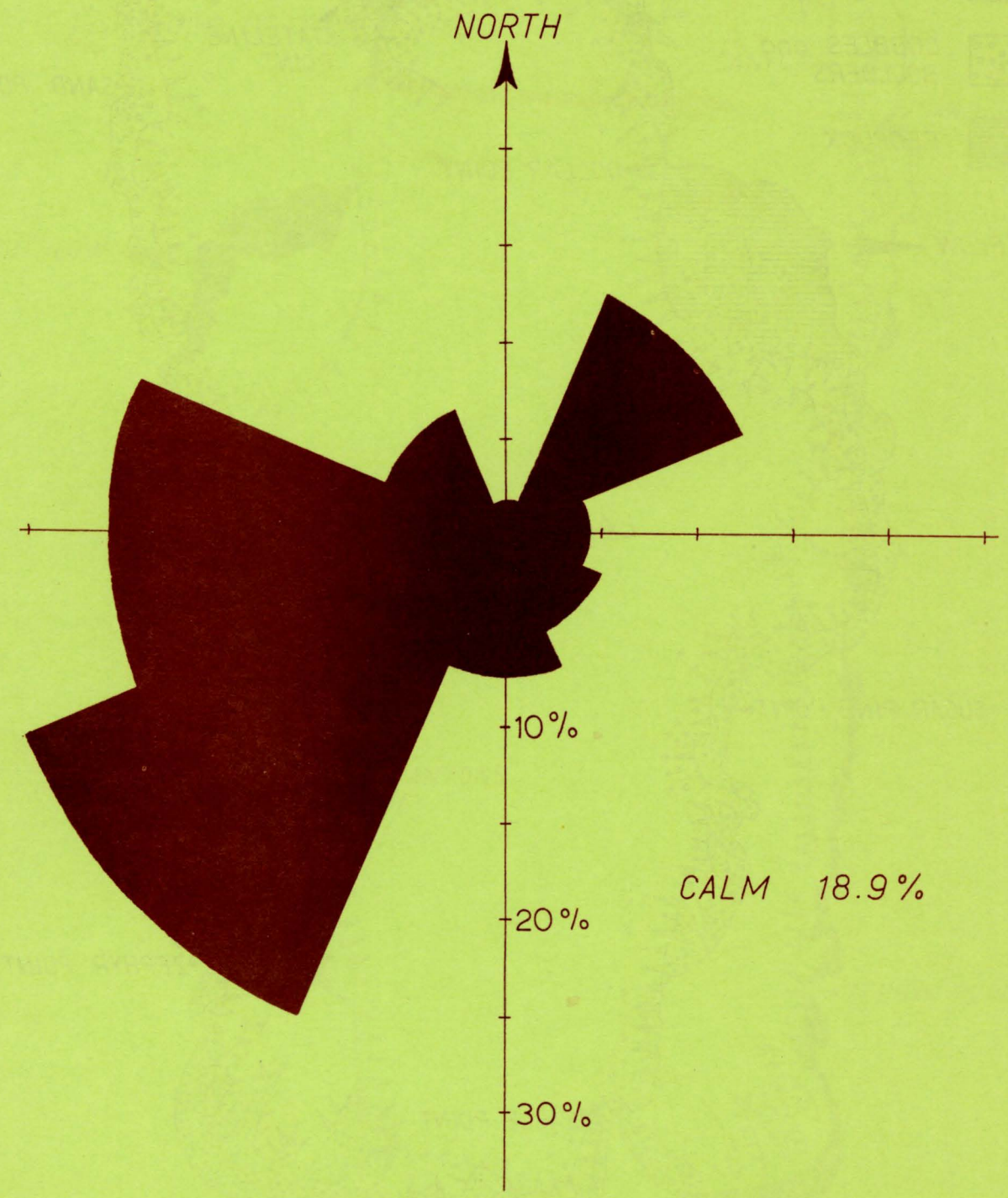


FIGURE 3. MEAN ANNUAL WIND ROSE, TAHOE CITY.

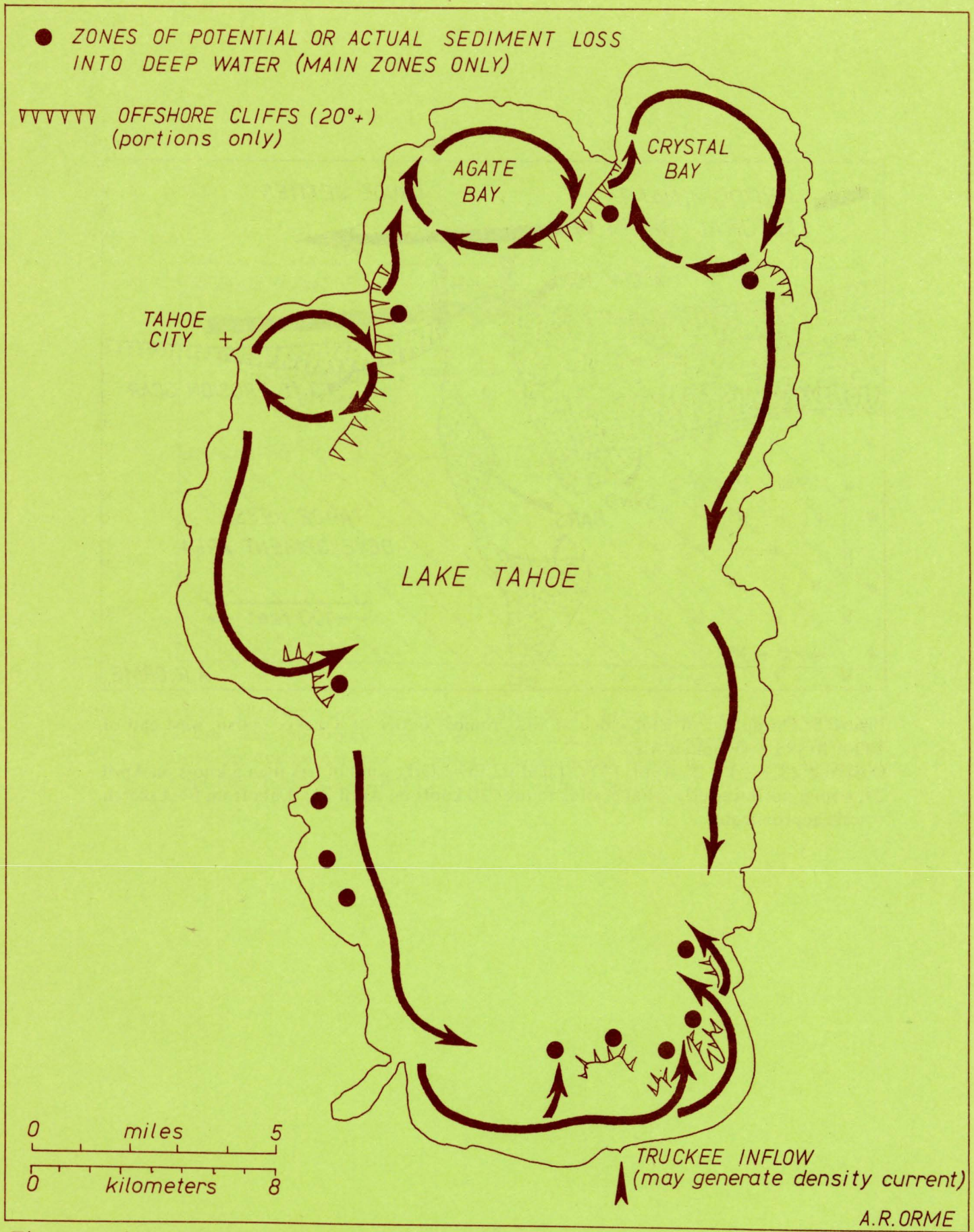


Figure 4. PREDOMINANT NEARSHORE CIRCULATION OF LAKE TAHOE

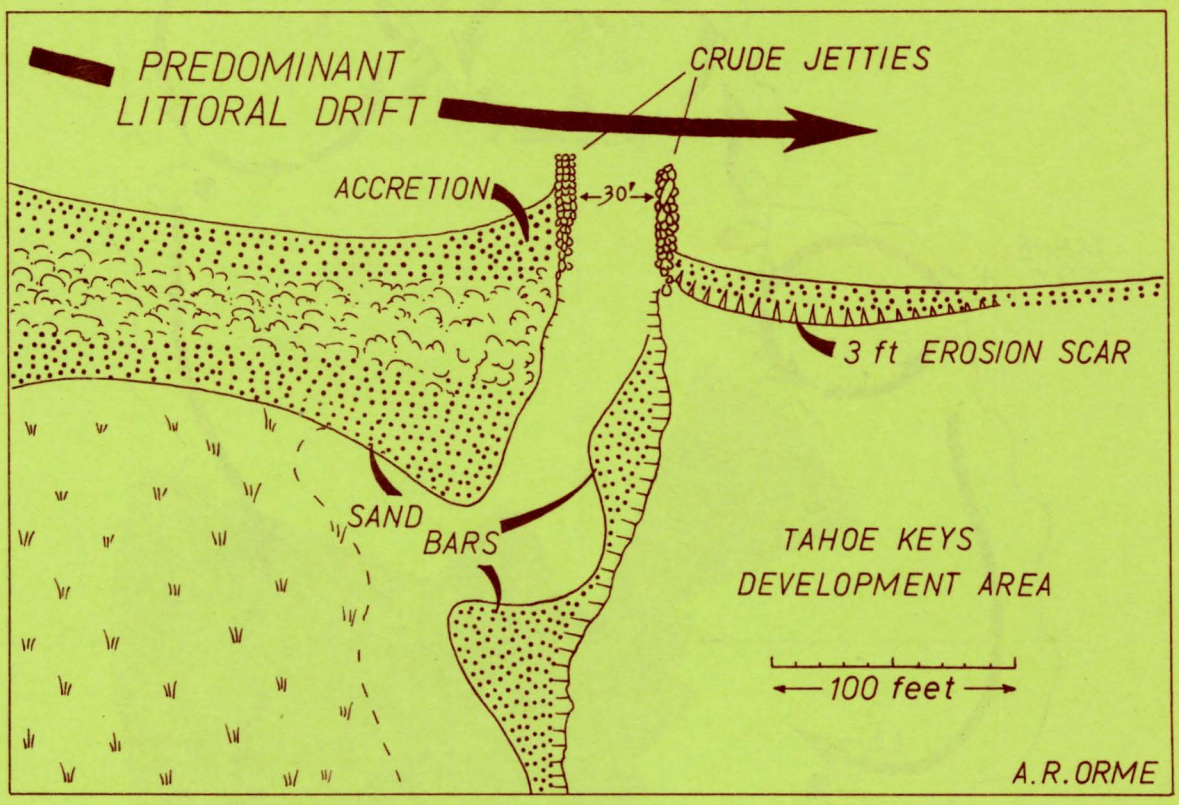


Figure 5. Disruption of shore-zone at westernmost outlet of Truckee Marsh, west end of Tahoe Keys Development Area.
Observed 23 – 24 – 25 April, 1971 (Light southwesterly wind of less than 5 knots on April 23; strong northwesterly wind gusting to over 30 knots on April 24). Data from field sketch – scale approximate.

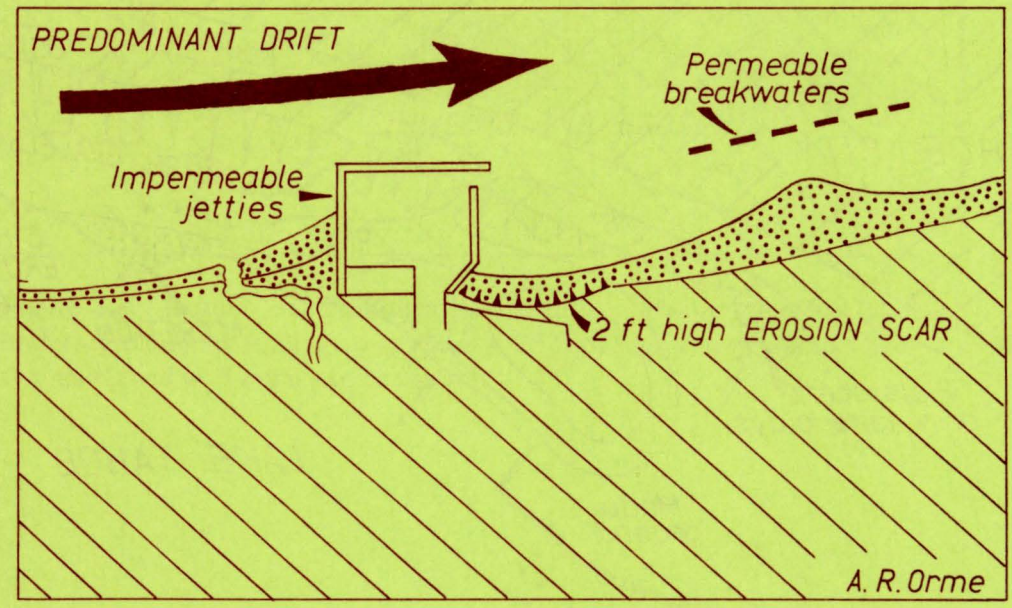


Figure 6. Shore-zone disruption at Lakeside Yacht and Harbor Club. Harbor jetties have encouraged accretion updrift and erosion downdrift. Permeable offshore breakwater has encouraged depositional bulge to form on shore opposite. Observed 24 April 1971; data from field sketch.

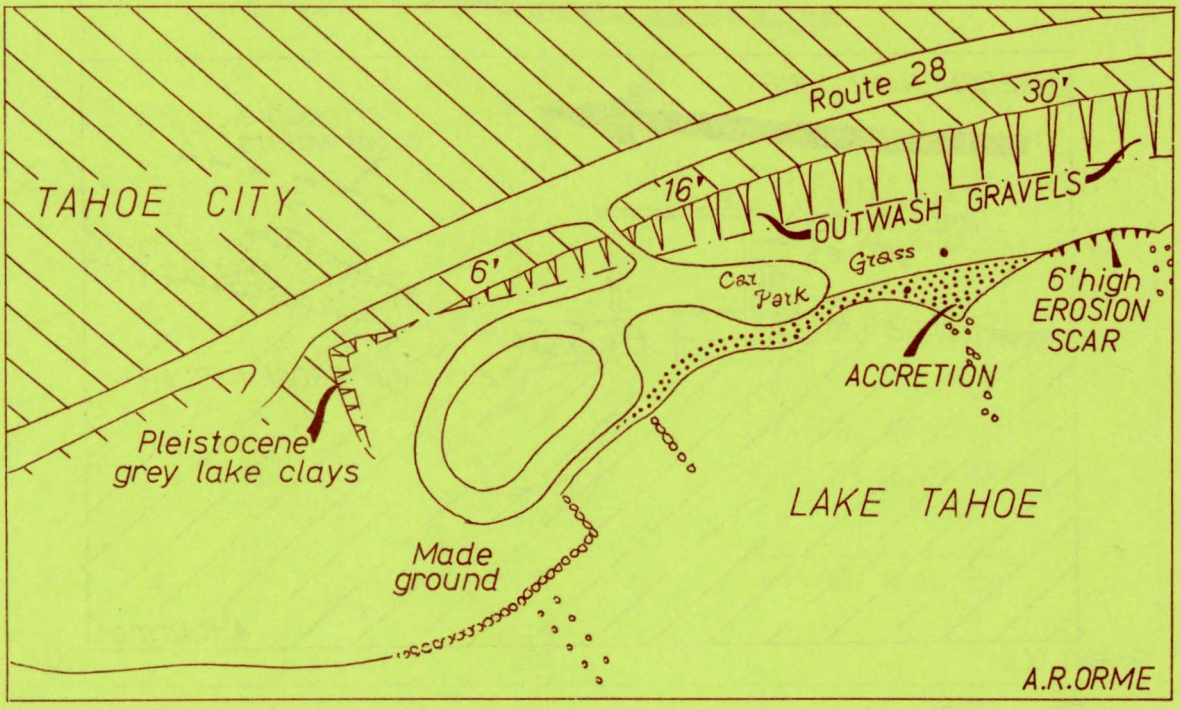


Figure 7. Man-induced shore-zone change northeast of the Truckee River outflow, Tahoe City. Natural accretion at the foot of an old lake cliff (composed of Pleistocene fluvioglacial outwash and lacustrine clays) has been augmented by man, but not without some loss through erosion towards the east end. Observed on 25 April, 1971; data from field sketch.

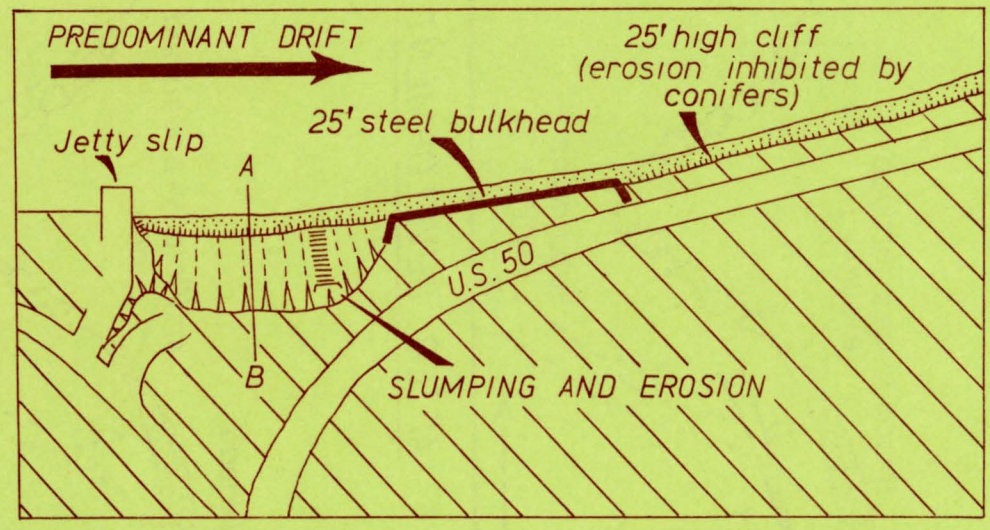


Figure 8. El Dorado Beach, South Lake Tahoe, showing the effect of beach undernourishment leading to erosion. A 25 foot high steel bulkhead protects the main road as it comes to the shore.

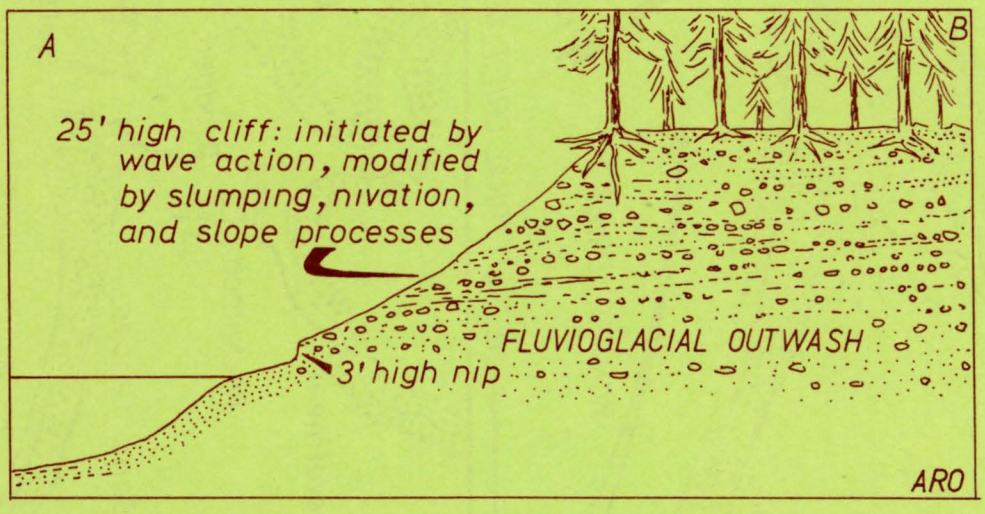
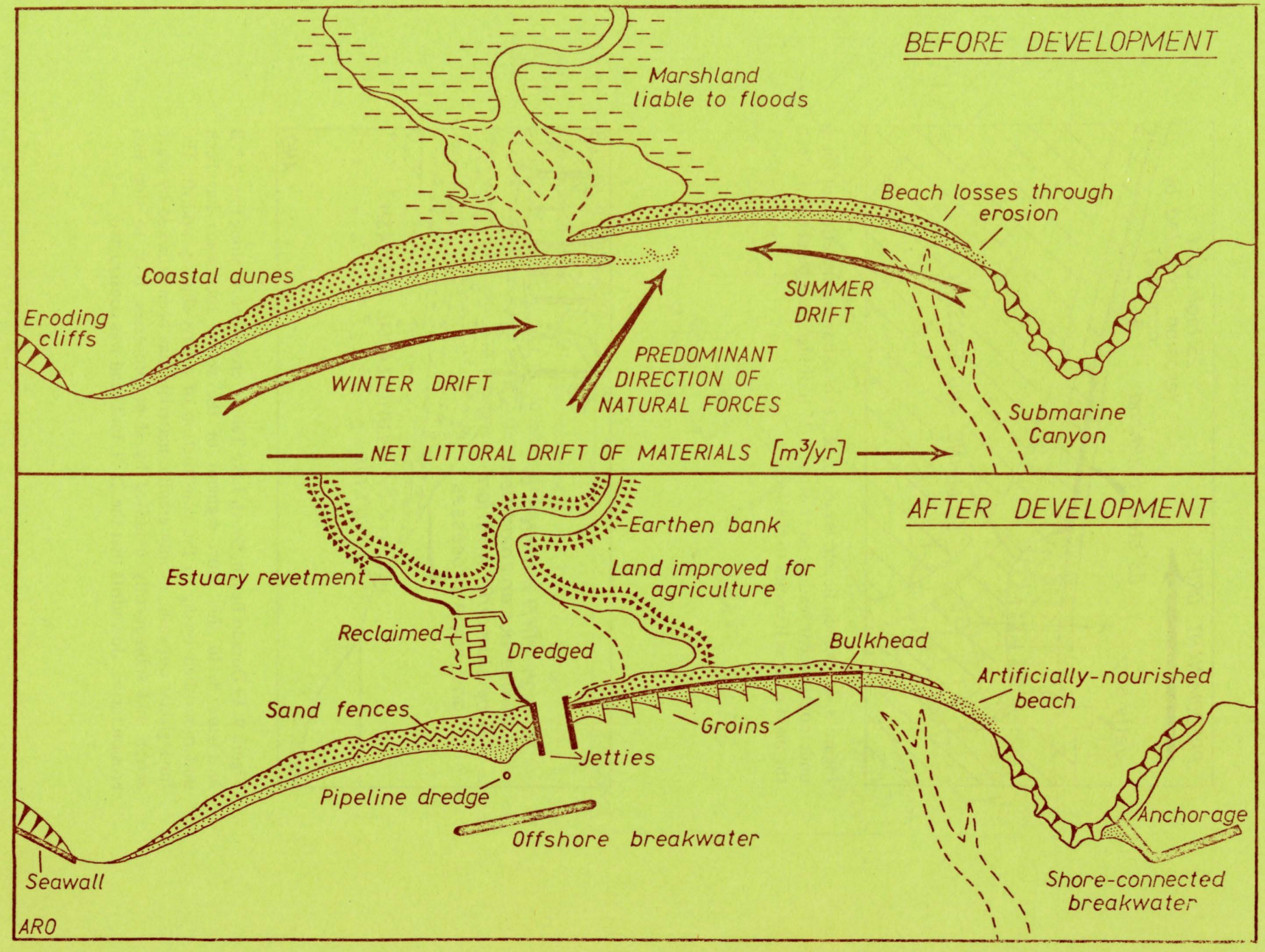


Figure 9. El Dorado Beach, South Lake Tahoe: cross-section along line A * B in Figure 8. In this short segment of the shore, the beach has been undernourished owing to the construction of a jetty-slipway updrift. The fluvioglacial outwash, mainly granitic materials, has been attacked by wave action and subsequently modified by slope processes. It is to stop this erosion farther downdrift that the 25 ft. bulkhead was constructed.

Figure 10. THEORETICAL REPRESENTATION OF A COASTAL ZONE BEFORE AND AFTER ENGINEERING CONSTRUCTION
(For information only - this situation does not relate to Lake Tahoe)



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